Uncertainties in transpiration estimates

ARISING FROM S. Jasechko *et al. Nature* **496,** 347–350 (2013)

How best to assess the respective importance of plant transpiration over evaporation from open waters, soils and short-term storage such as tree canopies and understories (interception) has long been debated. On the basis of data from lake catchments, Jasechko *et al.*[1] conclude that transpiration accounts for 80–90% of total land evaporation globally (Fig. 1a). However, another choice of input data, together with more conservative accounting of the related uncertainties, reduces and widens the transpiration ratio estimation to 35–80%. Hence, climate models do not necessarily conflict with observations, but more measurements on the catchment scale are needed to reduce the uncertainty range. There is a Reply to this Brief Communications Arising by Jasechko, S. *et al. Nature* **506,** http://dx.doi.org/10.1038/nature12926 (2014).

The selected values for runoff Q and interception xP in equation (4) of ref. 1 are low, resulting in high transpiration ratios. After consulting multiple state-of-the-art studies and using the mean and standard deviation (σ) of these estimates, we estimate Q at 39,600 ± 5,100 km^3 per year (refs 2–4) and xP at 20,100 ± 9,800 km^3 per year (refs 5–7), even without including understory interception[8]. The use of these more realistic input data lowers the transpiration ratio to 50–80% (Fig. 1b).

To estimate the isotopic composition of transpired moisture, δ_T is split between shallow and deep waters on the basis of normalized difference vegetation indices and precipitation. Although we agree that δ_T is difficult to estimate, we do not see a compelling physical reason for using this particular method to estimate deep δ_T, because the assumption that deeper water reflects the isotopic composition of rainfall has not been justified.

Rain water percolating to greater depths has to pass the unsaturated zone, where the isotopic composition of temporally stored water depends on evaporation (and thus fractionation) from interception storage (for example, forest floor[8]) and the topsoil[9]. Consequently, percolation through the unsaturated zone allows the rain water to mix with old, fractionated water, which results in deeper water having a different isotopic composition from rain water. Where preferential percolation through macropores is dominant, the assumption may be justifiable because water may bypass the soil matrix without significant mixing[9,10]. However, preferential percolation is not everywhere and always dominant.

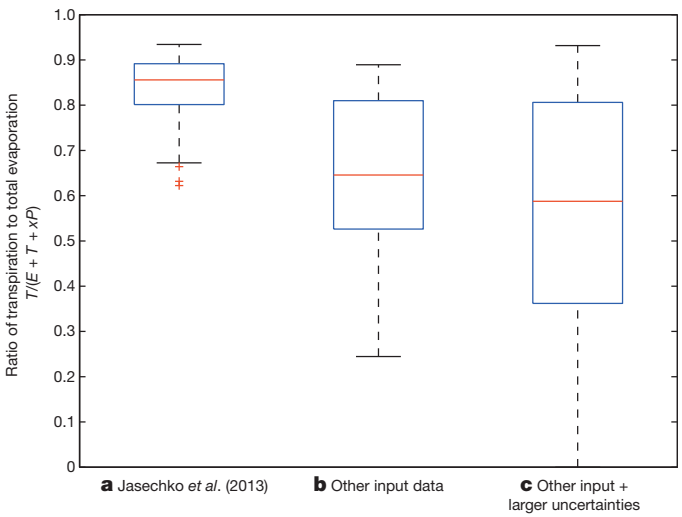

Figure 1 | Ratio of transpiration to total evaporation. **a**–**c**, Box plots are calculated using a simplified Monte Carlo simulation of equation (4)[1] with data from Jasechko *et al.*[1] (**a**), and with the same data as in **a** but with Q = 39,600 ± 5,100 km^3 per year and xP = 20,100 ± 9,800 km^3 per year (**b**), and with the same data as in **b** but with d_E = 75 ± 60‰ (**c**). The blue box indicates the 25th and 75th percentiles with the median in red. The error bars indicate the minimum and maximum values. The red crosses indicate outliers (3/2 times the central box).

Soil and open-water evaporation are isotopically grouped into one term and the estimate of the isotopic composition of evaporate is based on a very sensitive laboratory-derived evaporation model. The 'constant' C_K (equation (8) in ref. 1), however, depends on local climatic and physiographic conditions[11]. The applicability of this laboratory-derived model to global estimates has not been shown, nor has its sensitivity to the use of grid- and time-averaged values for the four inputs (T_A, h_A, δ_A and T_L) yet been assessed. The sensitivity analysis was performed with arbitrarily fixed values of σ for T_A, h_A, T_L and δ_A.

Besides the estimates of δ_T and δ_E (and thus d_T and d_E), we also consider the uncertainty ranges of ref. 1 far too optimistic. Performing an error propagation on the deuterium excess value, we find $\sigma^2(d) = \sigma^2(\delta^2H) + 8^2\sigma^2(\delta^{18}O)$. For $\sigma(\delta^2H_T) = 14‰$ and $\sigma(\delta^{18}O_T) = 1.7‰$ (Supplementary Table 4 in ref. 1), we find $\sigma(d_T) = 19‰$. Hence, it is not clear how the authors estimated $\sigma(d_T) = 3‰$. Accounting for all errors in equation (8) will result in a much higher estimate for $\sigma(d_E)$ than 30‰. Nonetheless, neglecting the propagation of errors and as an illustration just doubling the uncertainty in d_E, we find that the transpiration ratio decreases to 35–80% (Fig. 1c).

The fact that the transpiration ratio of ref. 1 aligns with a gross primary production estimate via the water-use efficiency (WUE) is not conclusive. First, the uncertainties in global WUE are high, owing to non-representative point measurements and the neglect of the underlying uncertainties in the WUE-regression relations (Supplementary Fig. 5 in ref. 1). Moreover, WUE varies in time, for example, owing to the CO_2-fertilization effect[12]. Second, gross primary production estimates are highly uncertain because gross primary production models often fail at the regional and global scale, owing to spatial and temporal heterogeneity, nonlinearity and site-specific data requirements[13]. Moreover, validating these models is problematic, because there are no direct measures at scales larger than the leaf level[14].

Although isotopes are useful for partitioning evaporation at the small scale[15], results at the larger scale are highly sensitive to the input data and their related uncertainties. Future improvements in observation techniques will enhance the application of isotopes to the partitioning of evaporative fluxes.

A. M. J. Coenders-Gerrits[1], R. J. van der Ent[1], T. A. Bogaard[1], L. Wang-Erlandsson[1,2], M. Hrachowitz[1] & H. H. G. Savenije[1]
[1]Water Resources Section, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands.
email: a.m.j.coenders@tudelft.nl
[2]Stockholm Resilience Centre, Kräftriket 2, SE 10691 Stockholm, Sweden.

1. Jasechko, S. *et al.* Terrestrial water fluxes dominated by transpiration. *Nature* **496,** 347–350 (2013).
2. Oki, T. & Kanae, S. Global hydrological cycles and world water resources. *Science* **313,** 1068–1072 (2006).
3. Dai, A. & Trenberth, K. E. Estimates of freshwater discharge from continents: latitudinal and seasonal variations. *J. Hydrometeorol.* **3,** 660–687 (2002).
4. Syed, T. H., Famiglietti, J. S., Chambers, D. P., Willis, J. K. & Hilburn, K. Satellite-based global-ocean mass balance estimates of interannual variability and emerging trends in continental freshwater discharge. *Proc. Natl Acad. Sci. USA* **107,** 17916–17921 (2010).

5. Wang, D., Wang, G. & Anagnostou, E. N. Evaluation of canopy interception schemes in land surface models. *J. Hydrol.* **347,** 308–318 (2007).
6. Dirmeyer, P. A. *et al.* GSWP-2: multimodel analysis and implications for our perception of the land surface. *Bull. Am. Meteorol. Soc.* **87,** 1381–1397 (2006).
7. Miralles, D. G., Gash, J. H., Holmes, T. R. H., de Jeu, R. A. M. & Dolman, A. J. Global canopy interception from satellite observations. *J. Geophys. Res.* **115,** 27 (2010).
8. Gerrits, A. M. J., Pfister, L. & Savenije, H. H. G. Spatial and temporal variability of canopy and forest floor interception in a beech forest. *Hydrol. Processes* **24,** 3011–3025 (2010).
9. Brooks, J. R., Barnard, H. R., Coulombe, R. & McDonnell, J. J. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. *Nature Geosci.* **3,** 100–104 (2010).
10. Hrachowitz, M., Savenije, H., Bogaard, T. A., Tetzlaff, D. & Soulsby, C. What can flux tracking teach us about water age distribution patterns and their temporal dynamics? *Hydrol. Earth Syst. Sci.* **17,** 533–564 (2013).
11. Kendall, C. & McDonnell, J. J. *Isotope Tracers in Catchment Hydrology* (Elsevier, 1998).
12. Keenan, T. F. *et al.* Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. *Nature* **499,** 324–327 (2013).
13. Yuan, W. *et al.* Global estimates of evapotranspiration and gross primary production based on MODIS and global meteorology data. *Remote Sens. Environ.* **114,** 1416–1431 (2010).
14. Welp, L. R. *et al.* Interannual variability in the oxygen isotopes of atmospheric CO_2 driven by El Niño. *Nature* **477,** 579–582 (2011).
15. Zhang, S., Wen, X., Wang, J., Yu, G. & Sun, X. The use of stable isotopes to partition evapotranspiration fluxes into evaporation and transpiration. *Acta Ecol. Sin.* **30,** 201–209 (2010).

Author Contributions All authors contributed equally, and all authors contributed to the data analysis.

Competing Financial Interests Declared none.

doi:10.1038/nature12925

Jasechko *et al.* reply

REPLYING TO A. M. J. Coenders-Gerrits *et al. Nature* **506,** http://dx.doi.org/10.1038/nature12925 (2014)

In their Comment, Coenders-Gerrits *et al.*[1] suggest that our conclusion that transpiration dominates the terrestrial water cycle[2] is biased by unrepresentative input data and optimistic uncertainty ranges related to runoff, interception and the isotopic compositions of transpired and evaporated moisture. We clearly presented the uncertainties applied in our Monte-Carlo sensitivity analysis, we reported percentile ranges of results rather than standard deviations to best communicate the non-linear nature of the isotopic evaporation model, and we highlighted that the uncertainty in our calculation remains large, particularly in humid catchments (for example, figure 2 in our paper[2]).

A global runoff flux of 37,288 km^3 per year was obtained from a previous compilation of discharge measurements[3], and has been independently reproduced within 1,300 km^3 per year (36,055 km^3 per year) using satellite measurements[4]. The larger uncertainty reported by Coenders-Gerrits *et al.*[1] ($\pm$ 5,100) is obtained using a higher runoff value from a schematic in a review[5], which also included direct groundwater discharge to oceans, making this number 10% higher than it should be. Because the uncertainty estimate recommended by Coenders-Gerrits *et al.*[1] also includes water fluxes not included in our runoff parameter, we stand by the original values used, which seem to us to be the best approximation of this uncertainty[3,4].

Global interception, derived from satellite measurements[6,7] (7,500 km^3 per year, as used in our paper[2]), global climate model outputs[8] (11,900 km^3 per year, shown in figure 6b of ref. 4) and stand-level measurements[9] (median value of 17.9% of precipitation, or 19,700 km^3 per year), all fall into a range from 7,500 km^3 per year to 19,700 km^3 per year. We note that the high end-member applied by ref. 1 is derived from stand-level measurements and was not intended to be used to estimate a global interception flux. Its use in this manner[1] introduces bias towards regions where interception is expected to be important, because interception measurements are not often reported in areas free of canopy cover.

The Comment[1] also suggests that the uncertainties we applied to the deuterium excess ($d = \delta^2H - 8\delta^{18}O$) of transpired moisture (d_T) and evaporate (d_E) were understated[2]. First, Coenders-Gerrits *et al.*[1] propose a deuterium excess uncertainty of $\pm$19‰ for transpired moisture, quoting the individual uncertainties in our paper in the $\delta^{18}O$ and δ^2H models. This uncertainty is too large because they do not recognize that $\delta^{18}O$ and δ^2H values covary[10], resulting in a well-constrained range of deuterium excess values for groundwater tapped by plant roots. The uncertainty we applied[2] for d_T ($\pm$3‰) is validated by a database of stable oxygen and hydrogen isotope values for shallow and deep groundwater across the continental USA (the Water Quality Portal, http://www.waterqualitydata.us). Samples from depths of $<$4.6 m—the global average rooting depth[11]—show a deuterium excess of 7.8 $\pm$ 4.1‰ (n = 1,021; 25th to 75th percentile range of data set), found to be nearly identical in deuterium excess to that of samples collected from depths greater than 4.6 m: d = 7.9 $\pm$ 3.1‰ (n = 24,309). These ranges are consistent with our estimate[2] of d_T of 8 $\pm$ 3‰. Coenders-Gerrits *et al.*[1] suggest that the deuterium excess value ascribed to evaporating moisture should be higher than $\pm$30‰. Our uncertainty of $\pm$30‰ was derived from the range of deuterium excess calculations for 73 lakes used in our study. We used percentile ranges so that the high sensitivity (and associated high uncertainty) would be carried through to our final, global scale calculation of transpiration and evaporation fluxes.

Finally, Coenders-Gerrits *et al.*[1] suggest that we neglect uncertainty in water-use efficiency (WUE), despite our use of the standard error of regression that resulted in a global WUE of 3.4 $\pm$ 0.9 mmol CO_2 per mol H_2O (ref. 2). CO_2 fertilization does indeed affect WUE[12], as we acknowledged[2], and continued research into WUE will allow us to monitor and map these changes as atmospheric CO_2 increases. We strongly disagree with Coenders-Gerrits *et al.*[1] that gross primary production models "fail at the regional and local scale," given the success of the FLUXNET project in constraining this vital component of the carbon cycle (123 $\pm$ 8 Gt of C per year reported[13]). Finally, WUE has in fact been measured at scales that are larger than the leaf level (see Supplementary Information refs 105, 114, 116 and 118 in ref. 2).

We do not agree with the magnitude of the increase in uncertainty in ref. 1, nor with the unidirectional changes to input parameters that produce lower transpiration fluxes. However, we agree with the final point of the Comment[1]: that further method development and the use of stable O and H isotopes in hydrology can help to reduce uncertainty in terrestrial evaporation and transpiration.

Scott Jasechko[1], Zachary D. Sharp[1], John J. Gibson[2,3], S. Jean Birks[2,4], Yi Yi[2,3] & Peter J. Fawcett[1]

[1]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA.
email: jasechko@unm.edu
[2]Alberta Innovates—Technology Futures, Vancouver Island Technology Park, Victoria, British Columbia V8Z 7X8, Canada.
[3]Department of Geography, University of Victoria, Victoria, British Columbia V8W 3R4, Canada.
[4]Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada.

1. Coenders-Gerrits, A. M. G. *et al.* Uncertainties in transpiration estimates. *Nature* **506,** http://dx.doi.org/10.1038/nature12925 (2014).

2. Jasechko, S. *et al.* Terrestrial water fluxes dominated by transpiration. *Nature* **496,** 347–350 (2013).
3. Dai, A. & Trenberth, K. E. Estimates of freshwater discharge from continents: latitudinal and seasonal variations. *J. Hydrometeorol.* **3,** 660–687 (2002).
4. Syed, T. H., Famiglietti, J. S., Chambers, D. P., Willis, J. K. & Hilburn, K. Satellite-based global-ocean mass balance estimates of interannual variability and emerging trends in continental freshwater discharge. *Proc. Natl Acad. Sci. USA* **107,** 17916–17921 (2010).
5. Oki, T. & Kanae, S. Global hydrological cycles and world water resources. *Science* **313,** 1068–1072 (2006).
6. Miralles, D. G., Gash, J. H., Holmes, T. R. H., de Jeu, R. A. M. & Dolman, A. J. Global canopy interception from satellite observations. *J. Geophys. Res.* **115,** D16122 (2010).
7. Miralles, D. G., De Jeu, R. A. M., Gash, J. H., Holmes, T. R. H. & Dolman, A. J. Magnitude and variability of land evaporation and its components at the global scale. *Hydrol. Earth Syst. Sci.* **15,** 967–981 (2011).
8. Dirmeyer, P. A. *et al.* GSWP-2: multimodel analysis and implications for our perception of the land surface. *Bull. Am. Meteorol. Soc.* **87,** 1381–1397 (2006).
9. Wang, D., Wang, G. & Anagnostou, E. N. Evaluation of canopy interception schemes in land surface models. *J. Hydrol. (Amst.)* **347,** 308–318 (2007).
10. Friedman, I. Deuterium content of natural waters and other substances. *Geochim. Cosmochim. Acta* **4,** 89–103 (1953).
11. Canadell, J. *et al.* Maximum rooting depth of vegetation types at the global scale. *Oecologia* **108,** 583–595 (1996).
12. Betts, R. A. *et al.* Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature* **448,** 1037–1041 (2007).
13. Beer, C. *et al.* Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. *Science* **329,** 834–838 (2010).

doi:10.1038/nature12926